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To: Dr. D. Mills
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TRIP REPORT
SIXTH INTERNATIONAL CONGRESS ON
APPLICATIONS OF LASERS AND ELECTRO-OPTICS
NOVEMBER 8-12, 1987, SAN DIEGO, CALIFORNIA

L. Mannik

Two of the conferences making up ICALEO (International Congress on Applications of Lasers and Electro-Optics) deal with electro-optic sensing and laser materials processing. The former was used to present a paper on the EPRI-sponsored development of a phosphor-based generator rotor temperature monitor. The latter represented an opportunity to learn about high power laser applications in the areas of cutting, welding and surface modification.

1. BACKGROUND

This year's International Congress on Applications of Lasers and Electro-Optics (ICALEO) brought together approximately 400 engineers and scientists from North America, Europe and Japan, to partake in three concurrent technical conferences as well as a small instrument exhibit. I participated in two of the conferences, Electro-Optic Sensing and Laser Materials Processing.

2. ELECTRO-OPTIC SENSING

Because of the many papers of interest in the Laser Materials Processing Conference described below, I was able to attend only a handful of papers at the Electro-Optic Sensing Conference, in addition to presenting a paper on the EPRI-sponsored project aimed at the development of a phosphor-based generator rotor temperature monitor. The summary of this paper is given in the Appendix.

Since the paper preceding mine was co-authored by two researchers at Oak Ridge, Steve Allison and Mike Cates, who have been very helpful in getting our phosphor thermometry research off the ground, I was looking forward to the opportunity of meeting one of them but unfortunately the paper was presented by one of the other six authors. This group has analyzed the accuracy of the phosphor temperature measurement technique as applied to the determination of jet turbine fan blade temperatures. Using the average of 100 samples they measured temperatures at 500 C with an uncertainty of ±0.5 C.

Prior to the conference I had encouraged Mei Sun, Director of Research at Luxtron Corporation, to attend the session on thermal sensing techniques. I felt that this would be a good opportunity to broaden our contact with this company which holds most of the patents in phosphor thermometry and which is the logical choice for a partner should the EPRI rotor temperature monitor proceed to the commercialization stage. I had a one hour meeting with Dr. Sun at the conference and learned that they are very interested in this application of phosphor thermometry, especially since several of their customers have expressed an interest in rotating surface applications. Two factors that would strongly influence Luxtron's decision to pursue commercialization are the potential market for a rotor temperature monitor and the cost of the product. I suggested that by the end of next year we would have a better handle on these factors after, hopefully, several months of testing of a prototype monitor being installed on a Nanticoke generator next March. The discussion also generated some useful technical information including alternate suppliers for lenses and fibers and indications that oxysulfide phosphors are prone to degradation under ultraviolet exposure and thermal cycling.

3. LASER MATERIALS PROCESSING

This was the best attended of the three conferences, attracting an audience of approximately 150 to hear an excellent set of papers which are highlighted below.

3.1 Cutting

Mike Sharp of PRC gave a well-reasoned presentation on the cutting capabilities of their 1.5 kW CO_2 laser, one of which was delivered to our laboratory last summer. He went over the arguments that led PRC to emphasize the mode quality of the output beam in their design and to develop the hyperpulse mode of operation, in which pulses are superimposed on a continuous output level. The resulting performance in cutting highly reflective materials like copper and aluminum is borne out by our own measurements with this laser/1/. I had several discussions with Mike at the conference, dealing mainly with technical aspects of laser welding, which we have recently been exploring.

A paper on "ultra-fine" cutting of sheet metal with a 450 W laser built by Amada Laser Systems in Japan emphasized the achievement of ~1 μm surface roughness in the cut edge by paying careful attention to the temporal and spatial stability of the laser as well as the precision of the workpiece motion system. An example of the latter is the use of an eddy current sensor to maintain the separation between the cutting nozzle and the workpiece at 0.5 ± 0.05 mm.

The American division of Amada has also investigated the fine cutting of metals, concentrating on the effect of laser beam quality on the cut quality, specifically the surface roughness. By measuring the high speed fluctuations in laser power and beam profile they have found that the best cuts are obtained with a high quality, stable beam combined with a vibration-free motion table. The peak to valley surface roughness can range from 3 μm to 10 μm, depending on the

stability of the laser output. They have evaluated eight different commercial lasers and presented results for three of these. Naturally, there was great interest in discovering the identity of the manufacturers of these lasers, which I managed to do by piecing together information gained from various attendees. The three lasers were from Coherent, Spectra Physics and PRC, and it was reassuring to note that the PRC laser demonstrated the best performance, although Spectra Physics was not far behind. In discussions with Amada, I learned that, while in the past they have tended to use Spectra Physics lasers in their systems, they are about to switch to PRC, partly because many of their customers require the pulsing capability which the Spectra Physics laser does not offer.

A paper from Imperial College dealt with the effect on cut quality of the relative alignment of the focussed laser beam and the gas assist nozzle. Apparently a misalignment amounting to 10% of the nozzle diameter can be tolerated before cut quality is adversely affected.

I spoke to several attendees about a subject of interest to Ontario Hydro's marketing representatives. One of the local steel companies has a need for cutting 14-cm thick steel billets which are at 900 C. The question is whether the elevated temperature would reduce the laser power requirements sufficiently to make feasible the cutting of such a thick section. I received conflicting responses from the various experts I consulted but the general feeling was that even if the power requirements were reduced somewhat, the cut quality of laser cutting at this thickness would be terrible at best. It was suggested that a laser could not complete with a plasma torch in this application. However, Gary Neiheisel of Armco Steel offered a different point of view. He felt that the development of a 1-kW Nd:YAG laser based on the slab design/2/, which is still taking place although several years behind schedule, offers the possibility of a sufficient depth of field to make the cutting of such thick materials feasible.

3.2 Welding

Several papers dealt with various aspects of heavy-section laser welding, defined as the joining of metal thicknesses greater than 0.25 in (6.4 mm). Such welding requires a minimum of 5 kW of laser power and in most cases closer to 10 kW. As a result, such studies are limited to the relatively few laboratories that have access to these high power levels.

Research at the Welding Institute (UK) investigated the efficiency of depositing laser energy into 10-mm steel during laser welding and found this to be ~50%. Researchers at United Technologies Research Center used their 15-kW laser to examine the stability limits of the weld pool in four welding configurations (vertical up, vertical down, overhead and downhand) for stainless steel plate in thicknesses up to 19 mm, the maximum thickness that could be welded in a single pass. Double pass welding was reported by Naval Research Laboratory as a method of improving the toughness or impact resistance of the welded piece, using a 12-kW laser and a 13-mm thickness of steel. Conventional pre- and post-heat treatment can give the same result but the laser method avoids heating the entire piece.

A paper from Westinghouse Marine Division on the laser welding of large stainless steel cylinders was less interesting for its technical content than for its message on the difficulty of implementing new technologies in the industrial environment. The presenter stressed the reluctance of industry to embrace new laser processing technologies, except for laser cutting. This results in prolonged design review and extensive qualification procedures. He claimed that far greater scrutiny is give to laser welding than other welding techniques and in one case it took 1½ years to get a particular application accepted after feasibility had been demonstrated. Another disquieting

statistic was that in his experience the cost savings associated with a new laser process had to approach 100% before it would be accepted by industry.

There was an interesting paper on non-metal welding presented by a glass technologist who had recently discovered the benefits of lasers. He described his extension of the only earlier example of the laser welding of glass he could find in the literature, a 1968 publication from NRC, using a 200 W CO_2 laser to make butt welds, windows, and ring seals in fused silica and borosilicate glass. He described the results as a solution looking for a problem and challenged the audience to find novel applications for this technology.

I made contact with Chris Dawes of the Welding Institute at the conference. Several people have suggested that it would be worthwhile for us to become a member of this research and consulting organization, and thereby gain access to the European perspective on welding. I later learned that we are currently engaged in negotiations concerning possible membership.

3.3 Hazards of Laser Cutting and Welding

A sobering presentation was made by researchers from the General Motors Institute who have analyzed the hazardous by-products produced by the laser cutting and welding of metal alloys and coated metals. It is well known that cutting plastics with a laser can produce hazardous fumes but it seemed to be less widely recognized that metal cutting and welding comes with its own set of hazards. For example, stainless steel contains 12 to 18% chromium, a toxic metal in oxide form.

The measured quantities of the by-products were compared to standards published by two US safety organizations, OSHA (Occupational Safety and Health Administration) and NIOSH (National Institute for Occupational Safety and Health). Such an analysis can be used to design appropriate ventilation rates to maintain concentrations at a safe level. One possible source of confusion is that NIOSH standards are consistently more stringent than the corresponding OSHA standards.

Based on the reaction to this paper, I got the impression that the industry has not paid enough attention to this aspect of laser materials processing. One positive sign was the presence at the conference of an exhibitor whose sole business is laser safety.

3.4 Surface Modification

A representative of the Japanese Welding Research Institute described research on the laser glazing of alloys using a pulsed YAG laser. This is a technique in which the focussed laser beam melts the surface, which subsequently undergoes rapid solidification, thereby forming an amorphous layer with improved metallurgical properties. In studies of a broad range of alloys, four types of results were identified, varying in the amount of the undesirable crystalline phase mixed in with the amorphous layer. The critical cooling rate Rc is defined as the cooling rate below which no amorphous phase is produced. Depending on the alloy composition, Rc ranges from 10^2 to 10^6K/s. In order to end up with a completely amorphous layer it is necessary to generate cooling rates two orders of magnitude greater than Rc by varying the laser pulse length and energy density.

Another difficulty with laser glazing, which was discussed in this paper and others, was the formation of cracks in the surface layer. Methods of avoiding cracking include pre-heating the surface and oscillating the laser beam over the surface.

Laser surface cladding usually involves the fusing of an alloy onto a metal substrate to yield improved corrosion and wear resistance. A paper from Iowa State University described the cladding of a ceramic onto a metal substrate using a carbon dioxide laser. A 1.5-kW laser was used to deposit a 60 thou (1.5 mm) film of zirconia (ZrO_2) onto a steel substrate. Laser cladding gives a more adhesive and less porous coating than plasma spraying. Further development to reduce cracking is needed before the process is ready for industrial applications. I spoke to Evan Van de Haar, who made the presentation, and made him aware of our interest in this technique as a possible method of coating pressure tubes or heat exchangers to increase their corrosion resistance.

3.5 Laser Developments

Mitsubishi presented a paper promoting their recently developed 5-kW CO_2 laser on the basis of its compactness (at 5 m^2, half the "footprint" of the previous model) as well as the controllability of its output power and mode pattern. It was interesting to note that in its lowest order TEM_{oo} mode, this laser's output is no greater than the PRC laser we are using (1.5 kW). Mitsubishi is extending their design to a 10 kW model in the near future.

A paper from General Electric dealt with the effects of using an optical fiber with the YAG laser. The interesting result was that the energy distribution of the beam emerging from the fiber was smoother and more symmetric than the input beam. According to the presenter, the only limit to the amount of YAG power that can be put through a fiber is the maximum output of current YAG lasers. In these experiments, the output of a 400 W YAG laser was propagated through a 9.5-m long silica fiber (800 μm core diameter) with a transmission of 90%, close to the 94% theoretical limit.

SUMMARY

ICALEO represents a good opportunity to cover at one conference two applications areas of current interest, electro-optic sensing and laser materials processing. It has the added advantage of attracting a size of audience (~400) that is small enough to permit ready interaction, yet large enough to represent a cross-section of researchers. At this year's ICALEO a paper was presented on the application of phosphor thermometry to generator rotor temperature monitoring and sessions on laser materials processing were attended which yielded a wealth of information and contacts.

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APPENDIX

The Application of Phosphor Thermometry to Generator Rotor Temperature Monitoring

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Abstract

The application of phosphor thermometry to generator rotor temperature monitoring over the range 60 to 150°C has been investigated, using measurements of the decay time of the visible emission stimulated in europium-doped yttrium oxysulfide by ultraviolet laser excitation. A prototype sensor suitable for field testing has been constructed, using optical fibers for light delivery and collection.

Introduction

The measurement of the surface temperature of the rotor in an electrical generator represents a challenge as well as an opportunity for remote temperature sensing techniques. Currently the only information available is an average rotor temperature inferred from a resistance measurement. A localized temperature sensor could provide an early indication of insulation breakdown which, if uncorrected, might result in a machine outage and extensive winding damage. As part of a project investigating the aging of insulation in rotating machines, the Electric Power Research Institute has for the past two years funded research on the application of phosphor thermometry to generator rotor temperature monitoring.

The application of remote phosphor thermometry to rotating surfaces has been pioneered by a team of collaborators from the Oak Ridge Laboratory Complex, EG+G Santa Barbara and Los Alamos National Laboratory. This research, much of which has been presented at previous ICALEO meetings[1,2,3], has demonstrated the versatility of the technique, which can measure temperatures ranging from 5°C to greater than 1000°C. The temperature is determined by measuring the decay time of the visible luminescence emitted by a phosphor in thermal contact with the object following excitation by ultraviolet light.

Commercial instrumentation has been available for many years based on measurement of the intensity or decay time of the luminescence from a phosphor bonded to the end of an optical fiber to form a small, electromagnetically inert temperature probe[4]. There has also been some research by the industry into non-contact thermometry using this approach[5].

The research at Ontario Hydro has resulted in the development of a prototype rotor temperature monitor which is ready for field testing. The design of the sensor is described and an experimental assessment is made of the effect that the generator environment may have on sensor performance.

Selection of Phosphor and Binder

There is relatively little information available on the temperature dependence of the decay time of the phosphor emission lines. However, since the decay time and intensity of the emission are expected to exhibit a similar dependence on temperature, data on the latter[6,7] can be used to select suitable phosphors for the temperature range of interest (60 to 150°C).

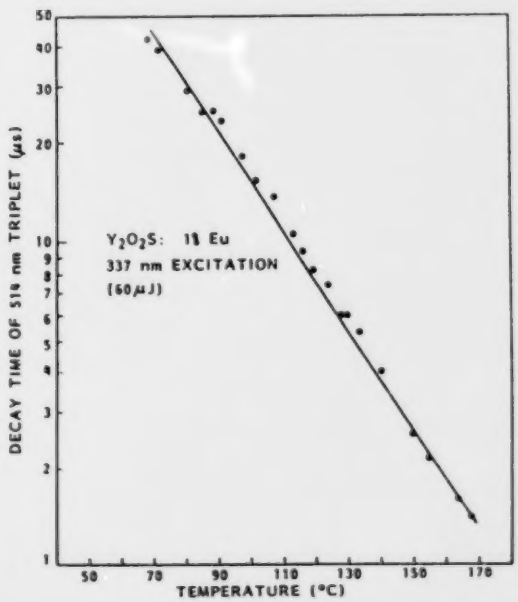

FIGURE 1
TEMPERATURE DEPENDENCE OF DECAY TIME OF 514 nm EMISSION IN EUROPIUM-DOPED YTTRIUM OXYSULFIDE

In this way two phosphors were selected for detailed evaluation: the $^5D_2$ emission band of Gd_2O_2S:Eu at 514 nm and the same band in Y_2O_2S:Eu. In each case the decay time was measured as a function of temperature using 337 nm laser excitation. For Gd_2O_2S:Eu the decay time varied from 30 μs at 60°C to <1 μs at 150°C. For Y_2O_2S:1% Eu the results are shown in Figure 1; the decay time ranges from 50 μs at 60°C to >2 μs at 150°C.

Primarily because of its longer decay time which simplifies data analysis and increases the accuracy at high temperatures, Y_2O_2S:Eu was chosen over the Gd_2O_2S:Eu phosphor. There are also advantages in terms of cost and availability. However, the differences are not great and we plan to use the Gd_2O_2S:Eu phosphor in selected spots on the rotor during the upcoming field tests.

Based on the two primary requirements, high temperature stability and ultraviolet transparency, the binder of choice was a silicone resin (Dow Chemical 806A) which could withstand temperatures of >200°C and which had a transmission of >90% at 337 nm.

Prototype Rotor Temperature Sensor

A prototype rotor temperature sensor has been constructed and tested in the laboratory using a 30 cm diameter aluminum disc rotating at 1725 rpm to simulate the rotor (Figure 2).

The selected phosphor powder (Y_2O_2S:1% Eu) was mixed with the silicone resin binder in a 2:1 ratio by weight (phosphor:binder) and applied to the disc in a thin layer (~75 μm). The mixture was smoothed with a block whose separation from the substrate was maintained constant by means of shims.

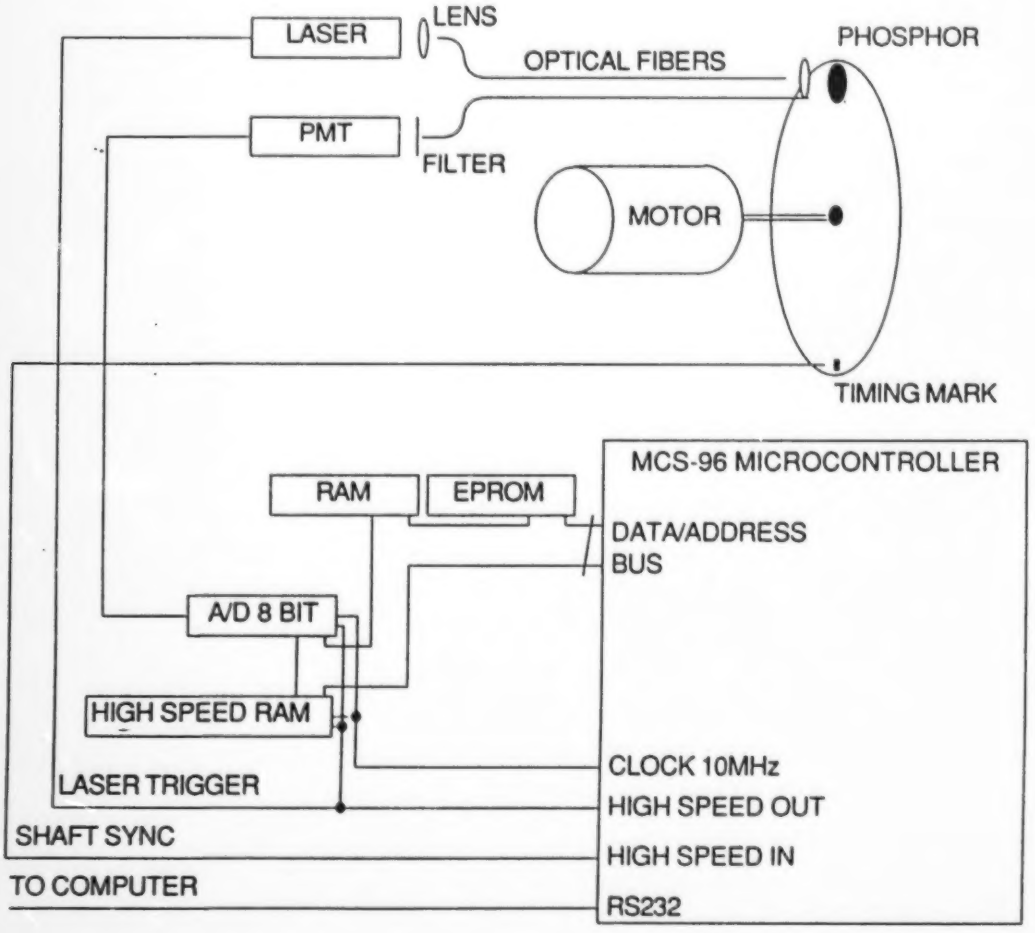

FIGURE 2

GENERATOR ROTOR TEMPERATURE SENSOR PROTOTYPE BLOCK DIAGRAM

The excitation source was a compact nitrogen laser (Laser Science Model VSL-337ND) which yielded >150 μJ pulses of ultraviolet output at 337 nm at a repetition rate of up to 20 Hz. This laser's low divergence (~1 mrad) makes it well suited for focusing energy into an optical fiber; with a 25 cm focal length lens the focused spot size is <500 μm. The laser is portable, weighing just 8 kg, and contains a gas cartridge which is replaced after ~10^7 shots.

The delivery fiber in the laboratory demonstration was a 15-m length of 600 μm diameter plastic clad silica fiber (General Fiber Optics). A 5.8-cm focal length lens focused the ultraviolet energy emerging from the fiber onto a 4-mm diameter section of the phosphor-coated surface 20 cm away from the end of the fiber. This separation was chosen to approximate the maximum separation expected in the rotor temperature measurement application.

A second identical fiber was used to collect the visible emission from the phosphor. To ensure that the field of view was broad enough to allow for motion of the phosphor spot during the decay time measurement, there was no lens between the collection fiber and the disc. For example, at 60°C the decay time is ~50 μs, during which time the spot would move ~10 mm. The output from the fiber passed through a 514 nm filter and, after collimation, was detected with a photomultiplier.

Data collection and analysis were performed with a microcontroller-based system designed and assembled in-house (Figure 2). An 8-bit 10 MHz A/D converter transforms the signal from the photomultiplier into digital form with a time resolution of 100 ns. This means that even at the highest temperature corresponding to the fastest phosphor decay there will be a sufficient number of points sampled to extract a decay time.

The digital signal is fed into an Intel MCS-96 microcontroller, a powerful single chip computer which performs all the calculations on the data and all input/output including user interface and data storage. This unit is capable of high speed arithmetic manipulation, eg two 16-bit numbers can be multiplied in 7 μs. Included on the chip are various input/output ports and two 16-bit counter/timers. One of the timers is used to synchronize the triggering of the laser to the rotation of the disc so that during a temperature measurement the laser acts as a stroboscope viewing the same phosphor spot on the disc. A reference signal for the synchronization is provided by a photodiode viewing a piece of tape attached to the backside of the disc. The triggering is performed with a resolution of 2.4 μs, which corresponds to a resolution in angle of 0.05° for a 60 Hz rotor.

There are two possible methods of extracting a decay time from the phosphor data. For each laser pulse a record of many samples (eg 1000) taken every 100 ns is stored in memory. In one approach this is repeated for many (up to 256) laser pulses and the results are averaged to yield a low noise waveform from which a decay time is extracted. Another option is to take a record of a single laser pulse and to use curve fitting techniques to deduce a decay time for each set of samples. The first approach would be more accurate but would require a longer time for data collection and would therefore result in earlier replacement of the laser cartridge. In either case the temperature is deduced from the decay time by means of a look-up table consisting of stored calibration data.

The microcontroller can be connected to an external computer via an RS232 port. During the development stage a computer will be used to output data and to coordinate the temperature monitoring program, ie which locations on the rotor are interrogated and in which sequence. In the final version of the sensor these functions would probably be handled by the microcontroller.

In terms of hardware, the laboratory demonstration temperature sensor described above is essentially ready to be used in field testing at an Ontario Hydro turbogenerator, scheduled for 1988. However, certain engineering areas remain to be addressed, such as designing a method of threading the optical fibers through the stator to reach the rotor and selecting an appropriate method of penetrating the generator housing which is pressurized with 3 atmospheres of hydrogen.

Effect of Generator Environment

In an effort to anticipate difficulties that might arise in field testing of the phosphor-based rotor temperature sensor, laboratory tests were devised to assess four aspects of the generator environment which could affect performance in the field. These are the elevated temperature, hydrogen atmosphere, magnetic field and the presence of generator oil.

Effect of Temperature and Hydrogen Atmosphere

A temperature controlled oven was filled with 3 atmospheres of hydrogen to simulate the environment in a tur-

bogenerator. Samples of Y_2O_2S:Eu and Gd_2O_2S:Eu phosphors mixed with silicone resin binder were prepared and applied to three types of substrates that may be encountered in rotor temperature monitoring: aluminum alloy (rotor wedges), silver-bearing copper (rotor windings) and forged steel (rotor teeth). These were placed in the oven at 100°C for six months, together with samples of five types of optical fiber, all with a silica core: (1) silicone polymer cladding, nylon jacket; (2) silica cladding, nylon jacket; (3) silicone polymer cladding, Teflon jacket; (4) hard silicone polymer cladding, Teflon jacket; (5) silica cladding, high temperature plastic jacket.

The phosphor samples showed no visible evidence of degradation, ie there was no discoloration or flaking. Three of the optical fibers (1, 3 and 5) experienced some shrinkage of the jacket material which resulted in the cladding becoming exposed. Typically the shrinkage amounted to 0.5 mm on each end of a 40-cm length of fiber. Fiber number 1 also experienced a 10% loss in ultraviolet transmission.

A further five months in the oven under the same conditions resulted in no further changes to the optical fibers.

These data will be used to select an optical fiber for the generator field testing. At this stage the choice has been narrowed down to fiber No 2 and fiber No 4, with the latter having a cost advantage ($14/m vs $60/m) while the former has a better ultraviolet transmission.

Effect of Magnetic Field

In a generator the phosphor will be exposed to a magnetic field of ~1 Tesla. Since the temperature dependence of the decay time is related to the position of the energy levels of the phosphor, it is possible that a magnetic field could disturb these levels and thereby alter the temperature dependence. Therefore, the temperature calibration of the Y_2O_2S:Eu phosphor was repeated in a magnetic field generated in the laboratory.

A 0.8 Tesla field was produced in the air gap of a split-core current transformer by passing a current of 50A through the coils. Two different samples were placed in the air gap. The first had the phosphor applied to a small piece of bakelite, chosen to minimize eddy current heating. This permitted a measure of the magnetic field effect at constant temperature, with the result that there was no difference in the decay time with the field on or off (50 ±1 μs at 22.5°C). In a second study, the phosphor was applied to an aluminum sample. In this case the magnetic field heated the sample up to 120°C, with the heating being slow enough that constant temperature measurements of the decay time could be recorded. Figure 3 shows the temperature calibration results for a 0.8 Tesla magnetic field together with the straight line resulting from the earlier zero field experimental data (Figure 1). There is evidently no significant effect of this magnetic field on the temperature dependence of the decay time.

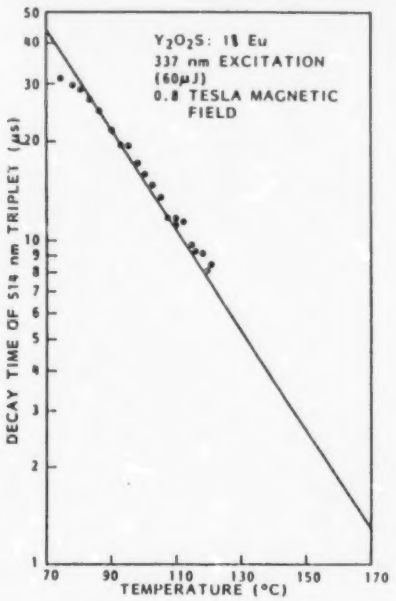

FIGURE 3

TEMPERATURE DEPENDENCE OF DECAY TIME OF 514 nm EMISSION IN EUROPIUM-DOPED YTTRIUM OXYSULFIDE IN THE PRESENCE OF A 0.8 TESLA MAGNETIC FIELD. THE SOLID LINE IS A LEAST-SQUARES FIT TO THE ZERO-FIELD DATA FROM FIGURE 1

Effect of Generator Oil

The environment inside a generator includes the presence of oil which originates from seals used to prevent the leakage of hydrogen cooling gas from the frame. Samples of used generator oil were obtained from two of Ontario Hydro's generating stations and their optical properties were measured.

A film of oil was deposited on the interior surfaces of an absorption cell by filling it with oil and allowing it to drain. Measurements of the transmission at the fluorescence emission wavelength (514 nm) and the ultraviolet exciting wavelength (337 nm) were performed using a uv-visible spectrometer.

The result was that the visible transmission was virtually unaffected by

the presence of the oil but the ultraviolet transmission dropped to a level of 60 to 70 per cent.

In a generator, the phosphor and fiber surfaces will be exposed to a hydrogen flow of ~10 m/s, which should reduce the thickness of the oil film compared to the laboratory tests. In any case, the ultraviolet absorption is not so severe as to undermine the feasibility of the technique.

Acknowledgements

This investigation was sponsored by the Electric Power Research Institute contract 2577-1, Bruce Bernstein, Project Manager. Greg Stone has been responsible for the coordination of this project. We are indebted to Stephen Allison and Michael Cates at Martin Marietta Energy Systems for sharing their knowledge of phosphor thermometry and for providing phosphor and binder samples. The Y_2O_2S:Eu phosphor used in these experiments was generously supplied by W.H. Fonger of RCA Laboratories. The assistance of Phil Labaj in the magnetic field measurements and of Dennis Mullins in the thermal aging tests is gratefully acknowledged.

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